DOE/NASA CONTRACTOR REPORT

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RESULTS OF THERMAL PERFORMANCE EVALUATION OF THE OWENS-ILLINOIS SUNPAK LIQUID SOLAR COLLECTOR AT INDOOR CONDITIONS

Prepared by

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For the U. S. Department of Energy

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Solar Energy

ACKNOWLEDGMENT

The test program covered by this report was requested by Mr. B. Wiesenmaier (EE01) and Mr. W. A. Hagen (FA33) of the George C. Marshall Space Flight Center. Mr. Wiesenmaier generated the test requirements and furnished technical coordination relative to application of ASHRAE 93-77 and the MSFC Solar Simulator to testing vacuum tube collectors.

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1.0 PURPOSE

The purpose of this document is to present the test procedures used during the performance of an evaluation test program. The test program was performed to obtain thermal performance data on the Owens-Illinois Sunpak solar collector under simulation conditions.

The test was conducted utilizing the MSFC Solar Simulator in accordance with the test requirements specified in Reference 2.1 and the procedures contained in Reference 2.2.

2.0 REFERENCES

2.1	ASHRAE 93-77	Method of Testing to Determine the Thermal Performance of Solar Collectors
2.2	MTCP-FA-SHAC-400	Procedure for Operation of the MSFC Solar Simulator Facility

3.0 COLLECTOR DESCRIPTION

Manufacturer:	Owens-Illinois
Manufacturer's Address:	P. O. Box 1035 Toledo, Ohio 43666
Type:	Sunpak - Evacuated Tube
Working Fluid:	Water
Gross Collector Area, Ft^2:	32.0
Overall External Dimensions:	Width, feet: 4.0 Length, feet: 8.0 Aperture Area, Ft^2: 27.4
Normal Tube Dimensions:	2 Inch Diameter x 44 Inches Long
Collector Glazing:	Evacuated Tube Cover Tube Transmittance Factor, .92 Absorber Tube Absorptivity Factor, .86 Absorber Tube Emissivity Factor, .07
Weight, lbs:	Empty: 110.0 Water Filled: 185.0

4.0 SUMMARY

This test program was performed to evaluate the thermal performance of an Owens-Illinois Sunpak liquid, evacuated tube, solar collector under simulated conditions. A schematic of the collector array is shown in Figure 1. The test conditions and the data obtained during the test program are listed in Table I for the thermal performance test and in Table II for the incident angle modifier test. A representative flux map is shown in Table III. In addition, a graphic presentation of the data obtained from the performance tests is shown in Figures 2 and 3. The transient effects of the solar incidence angle and the time constant on the collector are shown in Figures 4 and 5. Figure 6 defines the locations of instrumentation used in this performance program.

The only common ground for comparing overall collector performance should be the "all day efficiency" rather than $F_R\alpha\tau$. No standard practice has been established, but each collector should be evaluated for space heating, domestic hot water and solar cooling or process heat applications at a nominal location. This would assist the solar designer in choosing the most efficient collector for a particular application. Evacuated tube collectors are effective for solar cooling applications; therefore, according to the procedure in NBSIR 78-1305A, an all day efficiency for the Sunpak liquid collector was calculated for a typical solar cooling application. The selected site dependent data in conjunction with test results used in this determination are shown in Table IV.

The tests were performed on a module used on the early demonstration projects. A current production module is undergoing tests with results to be in a subsequent report.

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed at ambient conditions existing in Building 4619 at the time of the tests.

5.2 Instrumentation and Equipment

All test equipment and instrumentation used in the performance of this test program comply with the requirements of MSFC-MMI-5300.4C, Metrology and Calibration. Instrumentation locations on the test loop and collector are depicted in Figure 5. A listing of the equipment used in each test follows.

Apparatus	Manufacturer/Model	Range/Accuracy
Pyranometer	Eppley - PSP	0-800 $BTU/Ft^2 \cdot Hr \pm 3\%$
Liquid Loop	MSFC Supplied	.1 - 1.2 GPM
Directional Anemometer	Supplied by AMC	0 - 60 MPH
Flowmeter	Foxboro/1/2-2 81T3C1	.1 - .91 $\pm$ 1% GPM
Platinum Resistance Thermometer	Hy-Cal	0-500°F $\pm$ 0.5°F
Digital Printer	Doric Digitrend 220	0 - 500 MV $\pm$ 2%
Fans	MSFC Supplied	N/A
Solar Simulator	MSFC Supplied	See Reference 2.2
Pressure Gage	U.S. Gage Co./ Ashcroft	0 - 60 PSIG $\pm$ 1 PSI

The PSP pyranometer was calibrated by the manufacturer. The stated accuracy reflects the overall expected accuracy through the data acquisition system. A standard test setup is depicted in Reference 2.2.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 Collector Thermal Efficiency Test

6.1.1 Requirements

Utilizing the MSFC Solar Simulator and the portable liquid loop, parametric performance evaluation data shall be recorded of the following test variables and conditions. The liquid to be used is the manufacturer's recommended heat transfer fluid. If not specified, the test shall be performed using water as the working fluid. No preconditioning was necessary due to previous exposure.

Variable/Condition	Requirement
(1) Collector inlet liquid temperature differential above existing ambient temperature level	0°F, 25°F, 75°F, and 100°F
(2) Collector outlet liquid temperature	Measured data
(3) Incident solar flux level	250, 300 BTU/Hr·Ft^2 °F
(4) Liquid flow rate through collector	2.5 lbm/min (0.3 GPM)
(5) Wind speed	7.5 mph
(6) Ambient air temperature	Existing room condition

6.1.2 Procedure

1. Mount test specimen on test table at a 45° angle with reference to the floor.

2. Assure that simulator lamp array is adjusted to an angle of 45° with reference to the floor.

3. Using the procedure contained in Reference 2.2, align the test table so the test specimen's vertical centerline coincides with the vertical centerline of the lamp array and the distance from the loop of the test specimen to the lens plane of the lamp array is 9 feet.

4. Insulate all liquid lines.

5. Connect instrumentation leads to data acquisition system.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 Collector Thermal Efficiency Test (Continued)

6.1.2 Procedure (Continued)

6. Assure that data acquisition system is operational.
7. Perform sensor accuracy verification tests.
8. Establish required wind speed.
9. Start liquid flow loop and establish the required flow rate.
10. Establish the required inlet temperature.
11. Power up solar simulator in accordance with Reference 2.2 and establish the required solar flux level.
12. Record data for a minimum of five minutes at these stabilized conditions.
13. Repeat Steps 9 through 12 as necessary to complete all the required test conditions with independent tests as specified below.

Test No.	Inlet Liquid Temperature Differential Above Existing Ambient Temp., °F	Solar Flux BTU/Hr·Ft^2 °F	Liquid Flow Rate Lbm/Min.	Wind Speed, MPH
1	0	250	2.5	7.5
2	0	300	2.5	7.5
3	25	250	2.5	7.5
4	25	300	2.5	7.5
5	75	250	2.5	7.5
6	75	300	2.5	7.5
7	100	250	2.5	7.5
8	100	300	2.5	7.5

6.0 **TEST REQUIREMENTS AND PROCEDURES** (Continued)

6.1 **Collector Thermal Efficiency Test** (Continued)

6.1.3 **Procedure** (Continued)

14. Upon completion of testing, power down simulator and liquid loop in accordance with Reference 2.2.

6.1.3 **Results**

The results for the thermal efficiency test are contained in Table I and are presented graphically in Figures 2 and 3.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Incident Angle Modifier Test

6.2.1 Requirements

The collector incident angle modifier shall be determined by tilting the collector at 10°, 20°, 30°, 40° and 50° with respect to the solar simulator surface. The liquid flow rate shall be 2.5 lbm/min ± 0.10, with the inlet temperature controlled to within ± 2°F of ambient. The insolation rate shall be 300 BTU/Ft^2·Hr. The liquid to be used is the manufacturer's recommended fluid. If not specified, the tests shall be performed using water as the heat transfer medium. The following data shall be recorded during the tests.

(1) Collector tilt angles.

(2) Ambient air temperature.

(3) Collector inlet liquid temperature.

(4) Collector outlet liquid temperature.

(5) Collector differential temperature.

(6) Incident solar flux level.

(7) Liquid flow rate through the collector.

6.2.2 Procedure

1. Set up collector at required tilt angle.

2. Establish required flowrate.

3. Establish required inlet temperature.

4. Establish solar simulator flux level at 300 BTU/Ft^2·Hr and measure the flux levels at 24 locations on the collector surface and record on data sheet.

5. Record data for at least five minutes at above stabilized conditions.

6. Repeat above steps as necessary to obtain required data for each tilt angle.

6.2.3 Results

The results of the incident angle modifier test are presented in Table II and are shown graphically in Figure 4.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Time Constant Test

6.3.1 Requirements

The collector time constant shall be determined by abruptly reducing the solar flux to zero. This will be done with the inlet temperature adjusted to within ± 2°F of ambient while the liquid is flowing at 2.5 lbm/min.

The differential temperature across the collector shall be monitored to determine the time required to reach the condition of:

$$\frac{\Delta T(t)}{\Delta T_i} = .368$$

where $\Delta T(t)$ is the differential temperature at time t after the solar flux is reduced to zero and ΔT_i is the differential temperature prior to the power down of the solar simulator. The liquid to be used as the collector heat transfer medium shall be as specified by the manufacturer. If this liquid is not specified, use water as the fluid.

The following data will be recorded for the test:

(1) Solar flux.
(2) Ambient temperature.
(3) Inlet liquid temperature.
(4) Collector differential temperature.
(5) Liquid flow rate.
(6) Specified heat transfer medium.

6.3.2 Procedure

1. Adjust the liquid (water) flow rate to 2.5 lbm/min.

2. Adjust the inlet temperature to ambient ± 2°F.

3. Power up the solar simulator and establish a solar flux level of 300 $BTU/Ft^2 \cdot Hr$.

4. Establish wind speed of 7.5 mph.

5. Record data for ten minutes at above stabilized conditions.

6. Power down solar simulator.

7. Record the change of ΔT across the collector.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Time Constant Test (Continued)

6.3.3 Results

The results of the time constant test are shown in Figure 5.

7.0 ANALYSIS

7.1 Thermal Performance Test

The analysis of data contained in this report is in accordance with the National Bureau of Standards recommended approach. This approach is outlined below.

The efficiency of a collector is stated as:

$$\eta = \frac{q_u/A}{I} = \frac{\dot{m}\, C_{tf}\, (t_{f,e} - t_{f,i})}{I} \qquad (1)$$

where:

q_u = rate of useful energy extracted from the Solar Collector (BTU/Hr)

A = Gross collector area (Ft^2)

I = Total solar energy incident upon the plane of the solar collector per unit time per unit area ($BTU/Hr\cdot Ft^2$)

$\dot{m}$ = Mass flow rate of the transfer liquid through the collector per unit area of the collector ($Lbm/Ft^2\cdot Hr$)

C_{tf} = Specific heat of the transfer liquid ($BTU/Lb\cdot {}^\circ F$)

$t_{f,e}$ = Temperature of the transfer liquid leaving the collector (°F)

$t_{f,i}$ = Temperature of the transfer liquid entering the collector (°F)

Rewriting Equation (1) in terms of the total collector area yield:

$$\eta = \frac{(\dot{m}A)C_{tf}\,(t_{f,e} - t_{f,i})}{(IA)} = \frac{\dot{M}\, C_{tf}\,(t_{f,e} - t_{f,i})}{P_i} \qquad (2)$$

Notice that:

$P_i = IA$ = Total Power Incident on the Collector.

$\dot{m}A = \dot{M}$ = Total Mass Flow Rate through the Collector.

Therefore, $\dot{M}\, C_{tf}(t_{f,e} - t_{f,i})$ = Total Power Collected by the Collector.

7.0 ANALYSIS (Continued)

7.1 Thermal Performance Test (Continued)

Substitution in Equation (2) results in:

$$\eta = \frac{Pabs}{Pinc} \qquad (3)$$

where:

Pabs = Total collected power

Pinc = Total incident power

This value of efficiency is expressed as a percentage by multiplying by 100. This expression for percent efficiency is:

$$\text{Collector Efficiency} = \frac{Pabs}{Pinc} \times 100 \qquad (4)$$

or, from Equation (2), collector efficiency is defined by the equation:

$$\%\ \text{Eff.} = \frac{\dot{M}\ C_{tf}\ (t_{f,e} - t_{f,i})}{Pi} \times 100 \qquad (5)$$

Each term in Equation (5) was measured and recorded independently during the test. The calculated values of efficiency were determined at sixty-second intervals. The mean value of efficiency was determined over a five-minute period during which the test conditions remained in a quasi-steady state. Each five-minute period constitutes one "data point" as is graphically depicted on a plot of percent efficiency versus

$$\left((t_i - t_a)/I\right)$$

where:

t_i = Liquid inlet temperature (°F)

t_a = Ambient temperature (°F)

I = Incident flux per unit area (BTU/Hr·Ft^2)

The abscissa term $\left((t_i - t_a)/I\right)$ was used to normalize the effect of operating at different values of I, t_i and t_a. The results are found in Figure 2. Collector efficiency as a function of inlet temperature is shown in Figure 3.

The first order polynomial to best describe the test results is:
Efficiency = $a_0 + a_1 \Upsilon$

7.0 **ANALYSIS** (Continued)

7.1 **Thermal Performance Test** (Continued)

where:

$$\tau = (T_i - T_a)/I$$

and the coefficients for the configuration are determined to be:

Flow Rate (Lbm/Min)	2.5
a_0	0.496
a_1	-0.240

7.0 ANALYSIS (Continued)

7.2 Incident Angle Modifier Test

Two methods are proposed by ASHRAE 93-77 for incident angle modifier tests. For the MSFC Solar Simulator Facility, only method 1 (tilting the collector) is applicable. The collector was adjusted so that the incident radiation angles were 0°, 10°, 20°, 30°, 40°, and 50° to the normal of the collector surface. The collector was too large to tilt 60°.

According to 93-77, the incident angle modifier is defined as

$$K\alpha\tau = \frac{\eta}{F_R(\tau\alpha)n} \qquad (1)$$

where η = efficiency at tilted angle.

$F_R(\alpha\tau)n$ = Intercept of efficiency curve at normal incident angle = 0.496

For equation (1) to be applicable, the inlet liquid temperature must be controlled to within $\pm$ 2°F of the ambient air temperature. In cases where the inlet liquid temperature cannot be controlled to within $\pm$ 2°F, the following equation must be used to evaluate the incident angle modifier.

$$K\alpha\tau \; \frac{\eta + F_R U_L \dfrac{T_{f,i} - T_a}{I}}{F_R(\alpha\tau)\; n} \qquad (2)$$

where

$F_R U_L$ is the negative of the slope determined from the thermal efficiency curve, = 0.24

Table II shows that the inlet liquid temperatures were not all within $\pm$ 2°F of ambient air temperature. Hence, equation (2) was used for evaluation.

$$K\alpha\tau = \frac{\eta + 0.24 \dfrac{T_{f,i} - T_a}{I}}{0.496}$$

The results of this computation are shown in Table II and plotted against incident angle in Figure 4.

7.0 ANALYSIS (Continued)

7.2 Incident Angle Modifier Test (Continued)

The purpose of the incident angle modifier is to allow a designer or analyst to predict the total daily energy output from the collector, as the sun tracks from east to west. Most collectors are more efficient at normal incidence than at other angles, but some are even more efficient at angles other than normal. The only common ground for comparing collectors should be the "all day efficiency" rather than $F_R\alpha\tau$. However, the prospective application of the collector also influences the value of "all day efficiency." That is, for low temperature applications such as space heating or domestic hot water, a typical flat plate collector may have an all day efficiency of 40%, but for solar cooling applications the all day efficiency might be 20%. Therefore, criteria should be established to rate each collector for space heating, domestic hot water, and solar cooling at a nominal location, because efficiencies are also dependent on outdoor ambient temperatures.

Evacuated tubes are effective for solar cooling applications; therefore, according to the procedure in NBSIR 78-1305A the all day efficiency of the Sunpak for a typical solar cooling application is 30.6%. The selected site dependent data in conjunction with test data used in these determinations is shown in Table IV. No standard criteria has been established for "all day efficiency", and these calculations are dependent on system operating parameters, site data, time of year and daily weather; therefore, the above information should be viewed as interesting but not conclusive.

7.0 ANALYSIS (Continued)

7.3 Time Constant Test

Two methods are proposed by ASHRAE 93-77 for conducting a time constant test; however, due to facility limitations, the first method was used. This method consisted of shading the collector and maintaining a constant flow rate and inlet temperature while obtaining data.

According to the definition of time constant given in 93-77, it is the time required for the ratio of the differential temperature at time τ to the initial differential temperature to reach .368, when solar insolation is reduced to zero. It can be expressed as:

$$\frac{T_{f,e,\tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}} = .368 \qquad (1)$$

If the inlet liquid temperature cannot be controlled to equal the ambient air temperature, then the following equation must be used

$$\frac{F_R U_L\ (T_{f,i} - T_a) + \frac{\dot{m}C_p}{A_g}\ (T_{f,e,\tau} - T_{f,i})}{F_R U_L\ (T_{f,i} - T_a) + \frac{\dot{m}C_p}{A_g}\ (T_{f,e,ini} - T_{f,i})} = .368 \qquad (2)$$

where:

$T_{f,e,\tau}$	Exit liquid temperature at time τ
$T_{f,i}$	Inlet liquid temperature
$T_{f,e,ini}$	Initial exit liquid temperature
$\dot{m}$	Liquid mass flow rate, Lb/Hr
C_p	Specific heat of liquid, BTU/Lb·°F
A_g	Gross collector area, ft^2
$F_R U_L$	Negative of the slope determined from the thermal efficiency curve

The inlet temperature was maintained within ± 2°F of the ambient, hence equation (1) was used for evaluation. From Figure 6 the time constant was determined to be 20 minutes.

TABLE I

THERMAL PERFORMANCE TEST DATA FOR THE SUNPAK COLLECTOR

	300 BTU/Hr·Ft^2				250 BTU/Hr·Ft^2			
Ambient Air Temperature (T_a), °F	81.61	89.62	87.80	86.20	83.0	85.6	86.9	83.4
Fluid Inlet Temperature (T_i), °F	85.82	109.71	156.10	190.00	85.1	110.5	163.1	195.8
Fluid Outlet Temperature (T_e), °F	116.53	139.87	184.60	216.50	113.1	136.8	187.0	216.9
Differential Fluid Temperature (ΔT), °F	30.71	30.16	28.50	26.50	28.0	26.3	23.9	21.1
Total Solar Flux (I), BTU/Hr·Ft^2	292.73	297.40	297.40	297.40	256.6	256.6	256.6	248.4
Flow Rate, Lbm/Min.	2.50	2.40	2.40	2.40	2.55	2.45	2.50	2.50
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	.014	.067	.229	.349	.008	.097	.296	.452
Efficiency (η), %	.492	.456	.431	.400	.521	.471	.436	.398

TABLE II

INCIDENT ANGLE MODIFIER TEST DATA
FOR THE SUNPAK COLLECTOR

Angle	10°	20°	30°	40°	50°
Ambient Air Temperature (T_a), °F	83.9	83.4	83.5	84.1	87.3
Fluid Inlet Temperature (T_i), °F	86.1	86.0	86.0	86.1	86.4
Fluid Outlet Temperature (T_e), °F	114.6	110.5	106.9	104.3	103.7
Differential Fluid Temperature (ΔT), °F	28.5	24.4	20.9	18.2	17.3
Total Solar Flux (I), BTU/Hr·Ft^2	289.4	266.3	235.3	211.5	182.7
Flow Rate, Lbm/Min.	2.60	2.45	2.45	2.50	2.40
Efficiency (η), %	.480	.420	.408	.403	.424
Adjusted Efficiency Ratio $K\alpha\tau$	.970	.850	.827	.816	.854

TABLE III

REPRESENTATIVE FLUX MAP
RECORDED FOR SUNPAK COLLECTOR TEST

Tube No.	1	4	8	12	*
$BTU/Hr \cdot Ft^2$	304.3	286.1	274.9	263.8	A
$BTU/Hr \cdot Ft^2$	303.9	316.9	301.7	300.1	B
$BTU/Hr \cdot Ft^2$	286.1	279.0	282.3	292.4	C
$BTU/Hr \cdot Ft^2$	288.3	301.3	287.9	278.6	D
$BTU/Hr \cdot Ft^2$	289.0	319.5	304.6	297.2	E
$BTU/Hr \cdot Ft^2$	283.8	278.6	294.2	312.1	F

(Average Flux Recorded
292.7 $BTU/Hr \cdot Ft^2$)

* See Figure 1 for pyranometer locations.

TABLE IV
COMPUTATION OF SUNPAK ALL DAY SOLAR COLLECTOR EFFICIENCY

CALCULATION STEPS	HOUR OF THE DAY, SOLAR TIME												DAILY TOTAL
	6-7	7-8	8-9	9-10	10-11	11-12	12-1	1-2	2-3	3-4	4-5	5-6	
1. Inlet fluid temp. to collector, $t_{f,i}$	185	185	185	185	188	190	193	197	200	200	200	200	
2. Ambient air temp., t_a	73	74	79	82	86	90	92	93	94	94	92	90	
3. Incident radiation on collector plane, I_T (Table A2, ASHRAE 93-77)	6	60	132	197	249	281	292	281	249	197	132	60	2144
3a. $T_{fi}-T_a/I_T$	18.0	1.85	.80	.52	.41	.36	.35	.37	.43	.54	.82	1.8	
4. Collector thermal efficiency at normal incidence, determined in accordance with Sections 8.3.2 and 8.5 of ASHRAE 93-77 and using data from Lines 1, 2 and 3	0	.05 x	.30 x	.37	.40	.41	.41	.41	.39	.36	.30 x	.05 x	
5. Incident angle between direct solar beam and outward drawn normal to collector plane, θ d	90	75	60	45	30	15	15	30	45	60	75	90	
6. Incident angle modifier, determined in accordance with Sections 8.3.3 & 8.6 of ASHRAE 93-77 and using the value of θ from Line 5	0	.70 x	.86 x	.82	.83	.91	.91	.83	.82	.86 x	.70 x	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6]	0	2.1	34.0	59.8	82.7	104.8	108.9	95.6	79.6	61.0	27.7	0	656.2
8. Collector thermal efficiency, Line 7/Line 3													0.306

Example: 32°N Lat.
42° Tilt
Avg.- Clear Skies

x Estimated or Extrapolated Values

30.6%

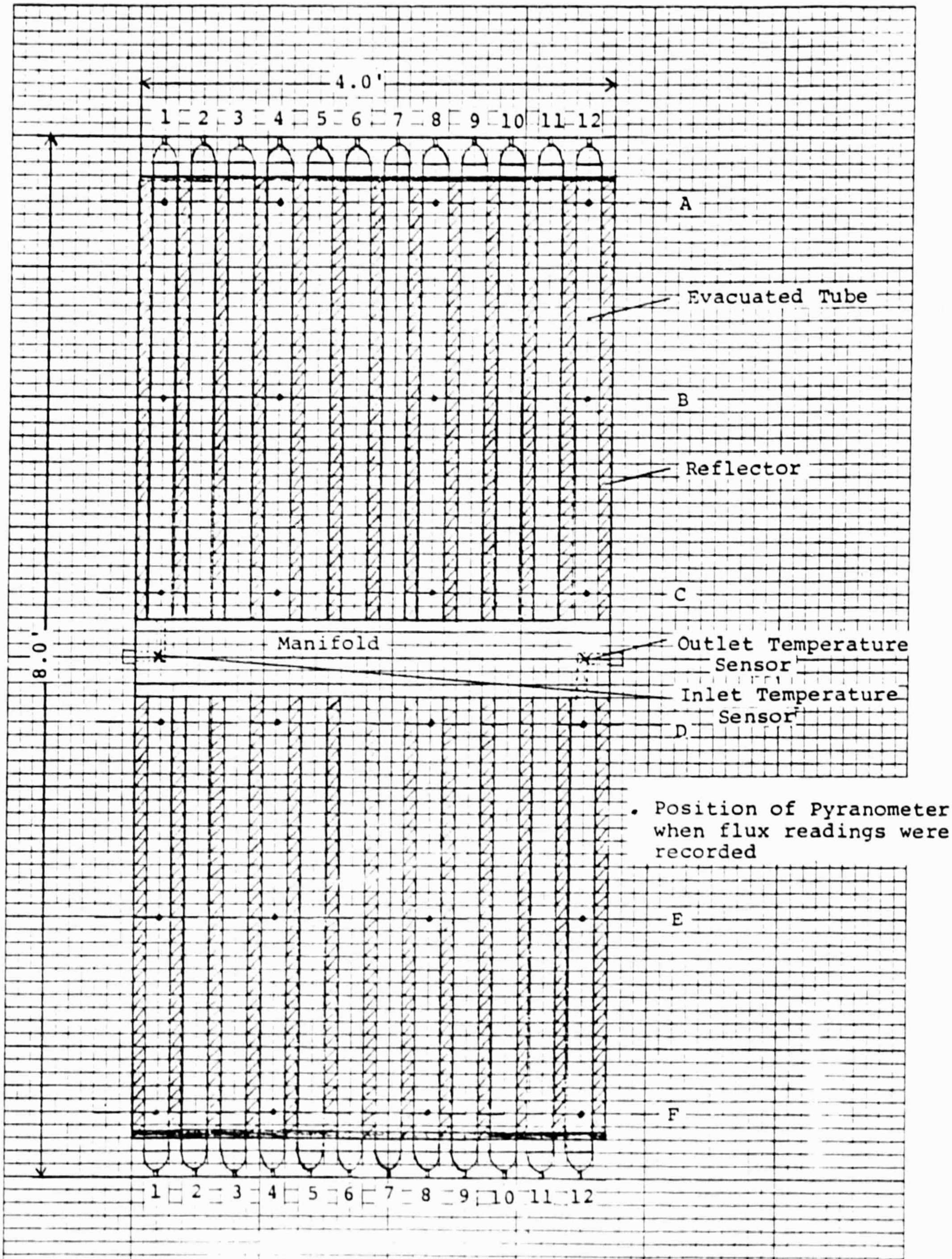

Figure 1. Sunpak Solar Collector Configuration

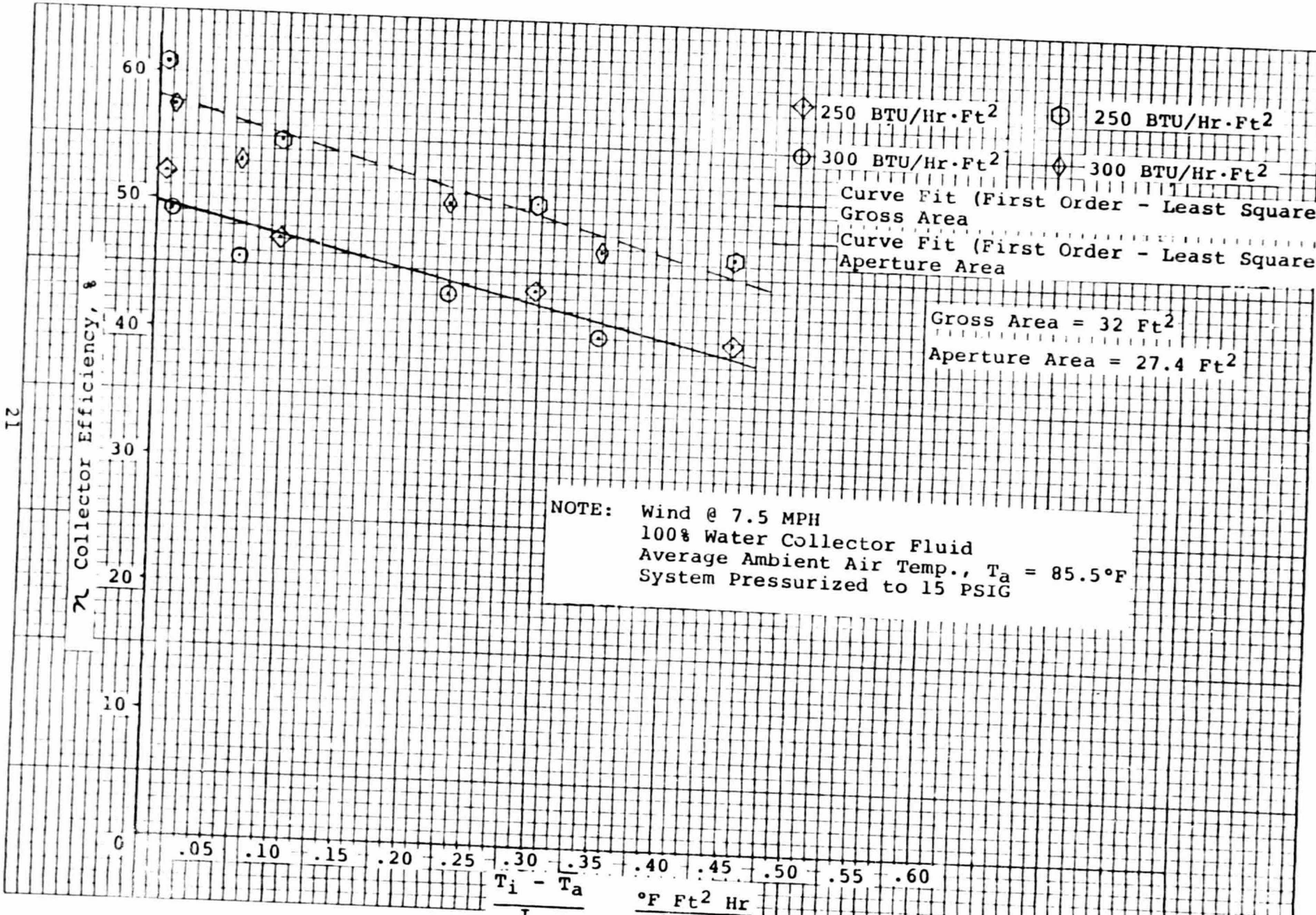

Figure 2. Thermal Efficiency of the Sunpak Liquid Solar Collector

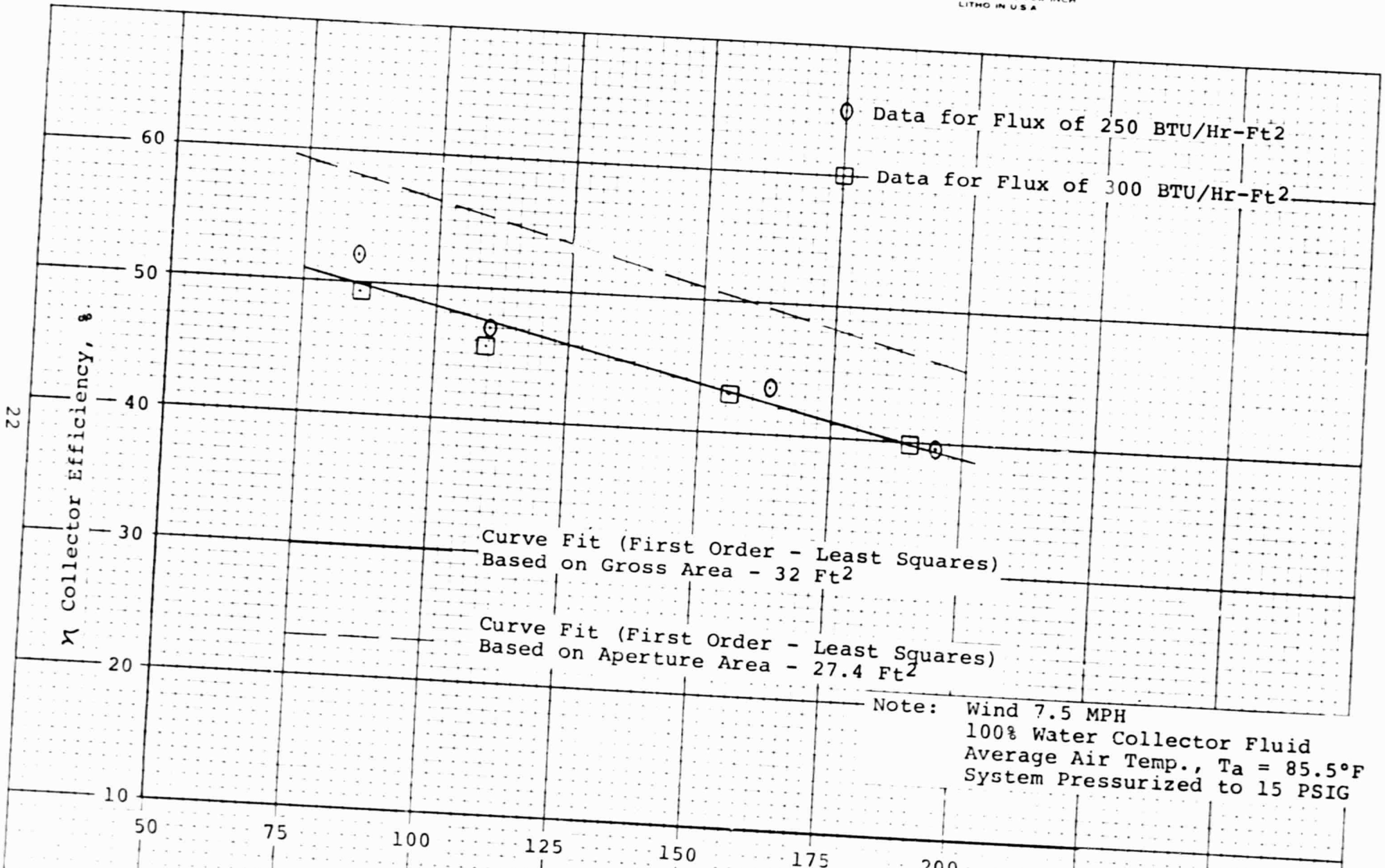

Figure 3. Collector Efficiency of the Sunpak Collector as a Function of Inlet Temperature

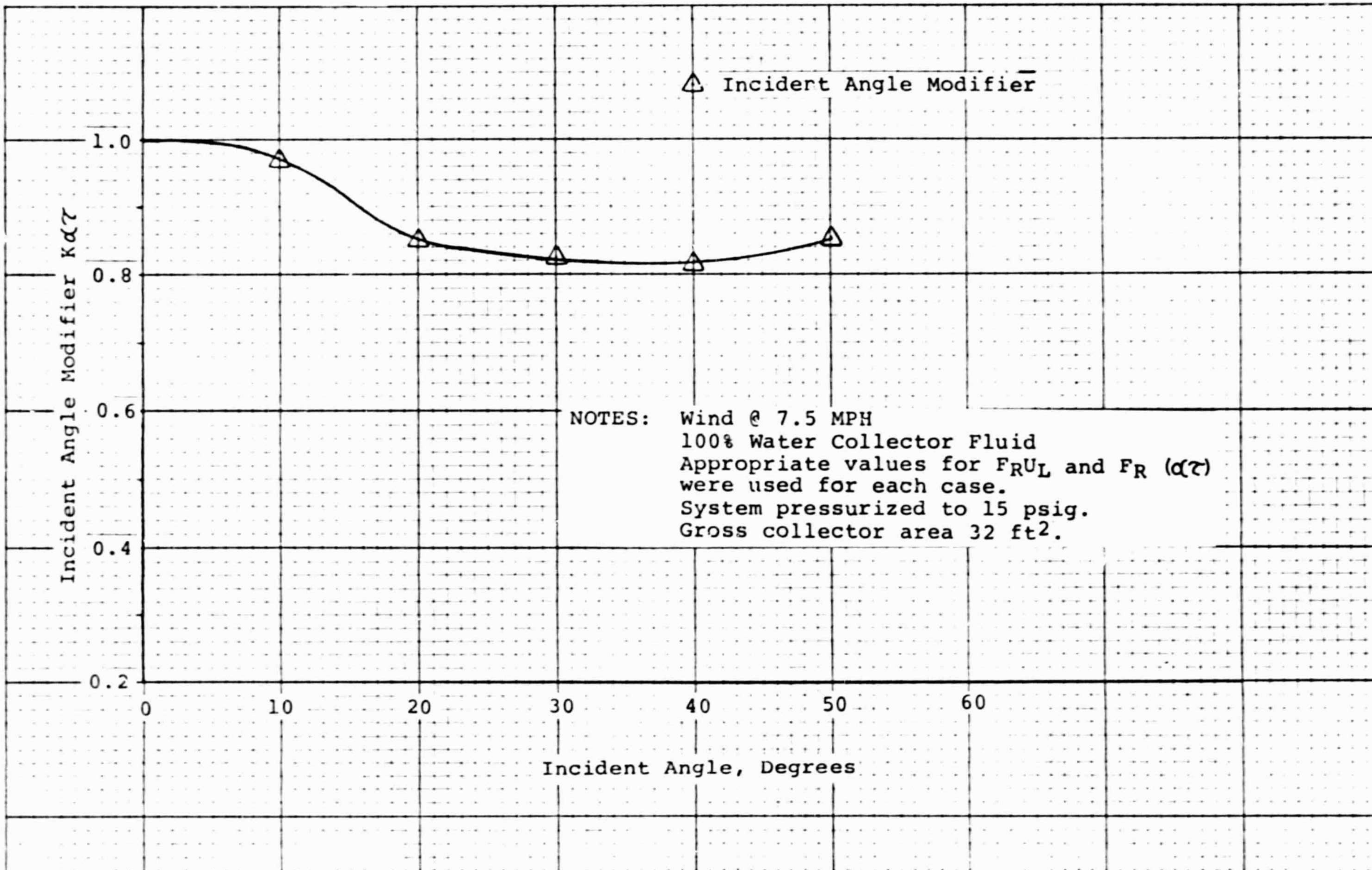

Figure 4. Incident Angle Modifier Test Results for the Sunpak Solar Collector

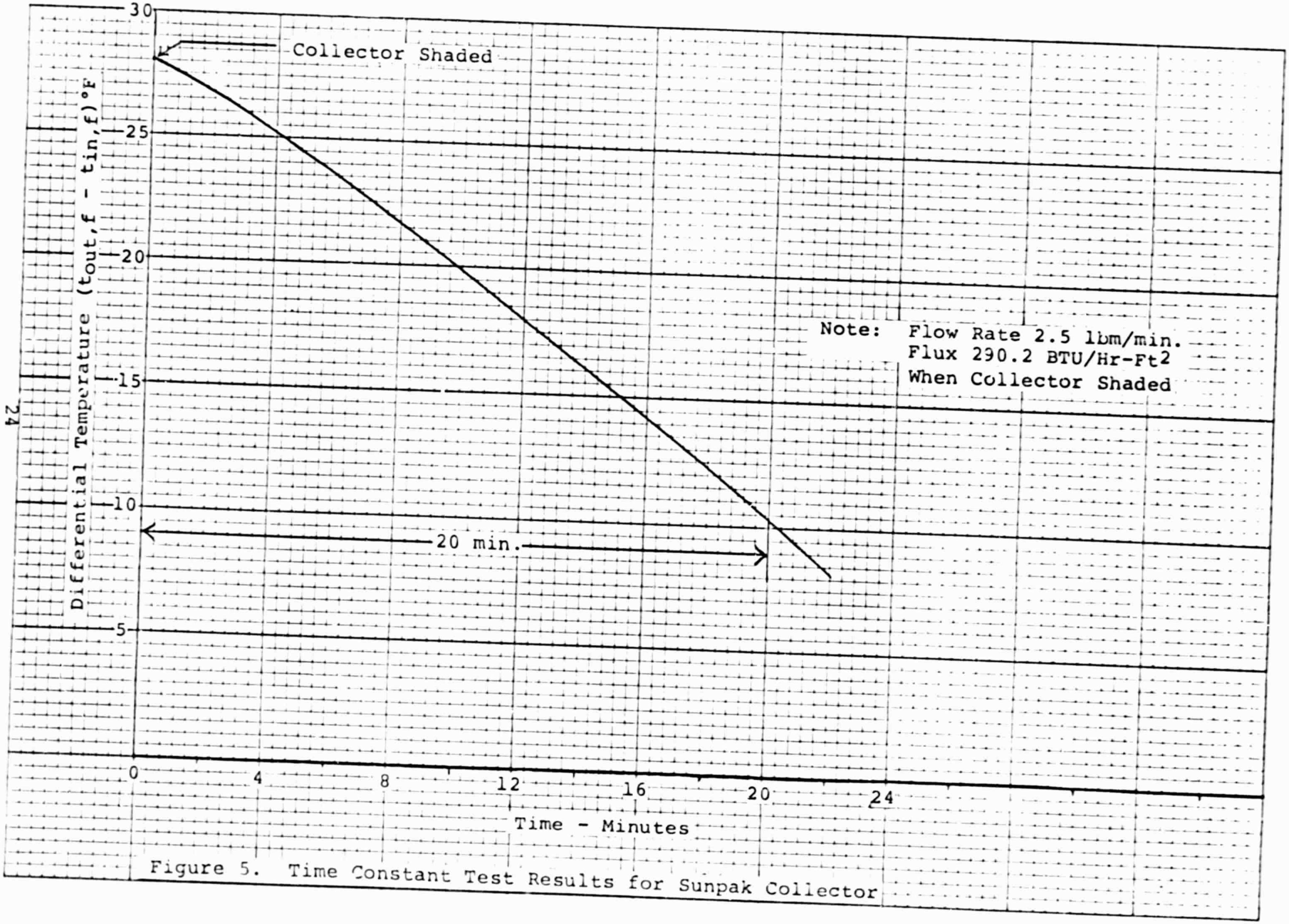

Figure 5. Time Constant Test Results for Sunpak Collector

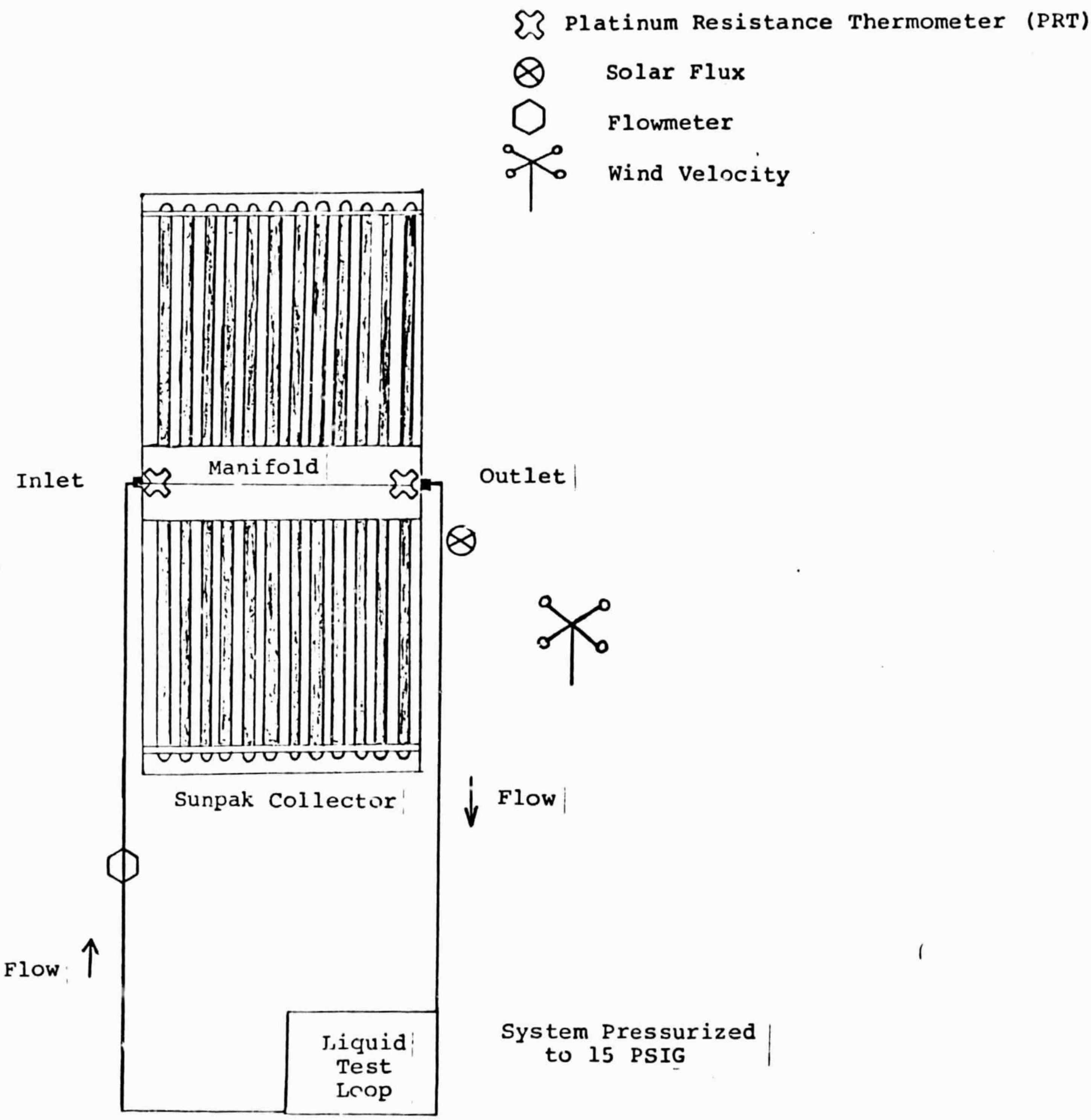

Figure 6. Instrumentation Locations for Liquid Collector Test